

BOUNDARY-LAYER FLOW VISUALIZATION FOR FLIGHT TESTING

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SUMMARY

Flow visualization is used extensively in flight testing to determine aerodynamic characteristics such as surface flow direction and boundary layer state. Several visualization techniques are available to the aerodynamicist. Two of the most popular are oil flows and sublimating chemicals. Oil is used to visualize boundary-layer transition, shock wave location, regions of separated flow, and surface flow direction. Boundary-layer transition can also be visualized with sublimating chemicals. A summary of these two techniques is discussed, and the use of sublimating chemicals is examined in some detail. The different modes of boundary-layer transition are characterized by different patterns in the sublimating chemical coating. The discussion includes interpretation of these chemical patterns and the temperature and velocity operating limitations of the chemical substances. Information for selection of appropriate chemicals for a desired set of flight conditions is provided. With the introduction of new aircraft utilizing laminar flow for drag reduction, flow visualization is an important diagnostic tool which supplements other analytical measurements for validation of aerodynamic design behavior.

INTRODUCTION

Past flight research has made extensive use of flow visualization for determining aerodynamic characteristics such as boundary-layer state (laminar, transitional, turbulent, or separated), shock wave location, and surface flow direction. Measurement of these characteristics becomes important to the aerodynamicist with the introduction of modern smooth aircraft surfaces which are compatible with laminar flow requirements. Flow visualization can be used for determining the boundary-layer transition characteristics while supplementing other analytical measurements for validation of aerodynamic design behavior.

Several techniques have been developed for in-flight flow visualization including sublimating chemicals (refs. 1 and 2) and oil flow (ref. 3). Each technique has its own advantages and disadvantages. The oil flow technique can provide information for a wide variety of flow conditions from boundary-layer transition to flow separation and shock wave location. At the same time oils can be very messy and must be viewed during flight. The sublimating chemical method provides a detailed pattern of boundary-layer transition that can be examined on the ground following the flight test. Whereas oil flow can show regions of laminar and turbulent separation, sublimating chemicals are far more

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 useful for determining transition modes including the cases of crossflow and Tollmien-Schlichting types of instabilities, as well as laminar separation.

The purpose of this paper is to describe the sublimating chemical technique for flow visualization. A method for selecting appropriate chemicals based on a set of flight conditions is provided. A brief description on the use of oils for flow visualization is included. The advantages of both flow visualization techniques for testing modern aircraft are discussed.

SYMBOLS

a	constant used in determining vapor pressure
b	constant used in determining vapor pressure
c	constant used in determining vapor pressure
g_s	rate of transfer of mass from unit area of surface, oz/s-ft ²
K_g	local mass transfer coefficient
m	molecular weight of a substance
m_∞	molecular weight of the free stream
M	Mach number
p	static pressure, mm Hg
p_s	absolute vapor pressure, mm Hg
R	recovery factor
R'	unit Reynolds number, ft ⁻¹
T	temperature, °C or °F

T_{aw}	adiabatic wall temperature, °C or °F
V_∞	free-stream velocity, fps
γ	specific heat ratio, $\gamma = 1.4$
ρ	density of diffusing vapor, slugs/ft ³
ρ_∞	free-stream density, slugs/ft ³
ψ	concentration, ρ/ρ_∞
ψ_∞	concentration in the free stream
ψ_s	concentration corresponding to saturation

SUBLIMATING CHEMICALS

Description of Technique

The chemical sublimation method for indicating boundary-layer transition was developed at the Royal Aircraft Establishment by W. E. Gray in 1944 (ref. 1). Originally devised for low-speed wind tunnel testing, the method was extended to aircraft in flight with the introduction of more durable coating materials. The sublimation method has the advantages of simplicity, rapidity, low cost in operation, and ability to provide a very detailed graphic record of the transition from laminar to turbulent flow over the surface. For many flight applications, the chemical pattern developed at the desired test condition can be viewed on the ground following the flight. The method has been effective at subsonic speeds for temperatures down to -20°F and altitudes up to about 20,000 ft and at supersonic speeds up to Mach 2 for temperatures down to -70°F and altitudes up to 55,000 ft (ref. 4).

The sublimation method for indicating boundary-layer transition involves coating the surface to be observed with a very thin film of a volatile chemical solid. During exposure to a free-stream airflow, areas develop in which the chemical film evaporates more rapidly due to greater local shear stress within the boundary layer as depicted in figure 1. Greater rates of sublimation will occur in regions of high shear stress or skin friction such as that found in turbulent flow. The regions near stagnation on the surface will also have high shear stresses and hence greater rates of sublimation.

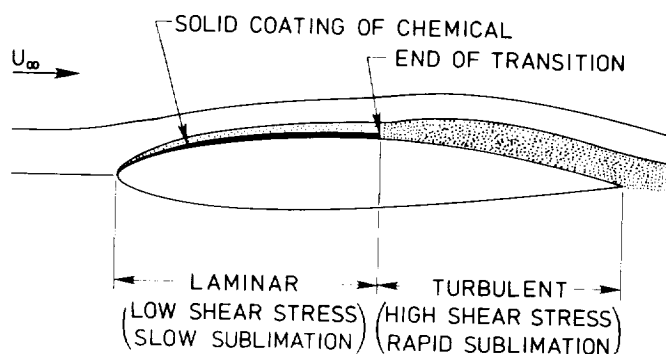


Figure 1.- How sublimating chemicals indicate boundary-layer transition.

There are several criteria necessary for the coatings to remain solid, opaque, and durable at temperatures for which transition indications are obtained and examined. The chemicals must have high melting points, be resistant to moisture, have no adverse effects on surface finishes, have low vapor pressures for aerodynamic use, and be soluble in a fast evaporating carrier. These considerations restrict the possible compounds to solids with melting points above 50°C , of low or

medium molecular weights, and high hydrogen content. The types of solid compounds suitable are hydrocarbons, esters, alcohols, ethers, ketones, acylamines, and azohydrocarbons (ref. 2). Another consideration for selecting appropriate chemicals is safety from health hazards associated with the use of such compounds. Four useful compounds which meet these requirements and provide a practical range of operating characteristics (sublimation rates) are naphthalene, biphenyl, acenaphthene, and fluorene, listed in Table 1. An added feature of fluorene is its fluorescent properties, which make it possible to obtain high quality photographic transition pattern data by using ultraviolet lighting.

Table 1. Practical Sublimating Chemicals for Transition Visualization

Chemical Substance	Chemical Formula Molecular Weight
Naphthalene	C_{10}H_8 128.17
Biphenyl	$\text{C}_6\text{H}_5\text{C}_6\text{H}_5$ 154.21
Acenaphthene	$\text{C}_{10}\text{H}_6-1,8-\text{CH}_2\text{CH}_2$ 154.21
Fluorene	$\text{C}_6\text{H}_4\text{CH}_2\text{C}_6\text{H}_4$ 166.22

The solvents used must have low toxicity, low corrosiveness, and high volatility. Water and the low-volatility alcohols have insufficient vaporizing characteristics to be used as solvents. Some of the esters which are low in toxicity are corrosive to metals in long-term use. The solvents found to be most suitable are acetone

and light petroleum fractions such as 1,1,1 trichloroethane and trichlorotrifluoroethane (Freon TF). The requirement for a highly volatile solvent is a result of the process by which the sublimating chemicals are applied to the surface. A technique called "dry-spraying" is used whereby the chemical solute is dissolved in the solvent and the solution is sprayed onto the surface. It is necessary that the solvent be almost completely evaporated before the spray solution has time to wet the surface, leaving the sublimating chemical coating on the surface.

The chemical is applied to the test surface by compressed-air spraying. A solution of 8 parts solvent to 1 part solute (by volume) has been found to be nearly optimum for uniform application. The solution is ready for spraying when the solute has completely dissolved. When using standard compressed-air spray equipment, good control in uniform thickness of the chemical coating is best achieved using a spray gun with a flat fan nozzle of minimum size orifice and needle (orifice diameter between 0.030 and 0.040 in.). Spraying is done using about 25 psi air pressure, for either siphon feed or pressure feed equipment. If pressure feed equipment is used, the reservoir pressure should be about 5 psi. The spray nozzle should be held between 10 to 20 in. from the surface being coated for proper dry-spraying. Proper spray technique will produce a powdery matte appearance of the chemical coating, whereas when the spray goes on too wet, the coating appears crystalline. After spraying, the chemical coating is brushed with a large soft bristle

brush, wiped with cheesecloth, and rubbed by hand (using rubber gloves) to loosen chemical particles which can adhere to the coating and cause turbulent wedges.

A standard rate of chemical solution application is one quart per 20 to 30 ft². At the application rate of 20 ft² per quart, a very heavy coating will result. Depending on temperature and airspeed, such a coating thickness has a sufficiently long reaction time to permit ample off-condition flight time for takeoff, climb, descent, and landing without affecting the chemical pattern developed at the test condition. This feature permits transition data to be observed and recorded on the ground. Extra thick coatings can be applied by brushing the surface between repeated applications of a "standard" thickness. This technique can be useful for thick applications of rapidly sublimating chemicals to extend the allowable off-condition time for climb to high altitude test conditions, for example.

During the test flight, airspeed and altitude should be held as long as needed to obtain a transition pattern. If the fuel burn at the test condition changes airplane weight by more than about ten percent, a speed schedule should be worked out to keep the airplane lift coefficient constant (for conditions where compressibility can be ignored). For high-speed tests where compressibility is a factor, an altitude schedule should be flown to maintain a constant Mach number at constant indicated airspeed. For most flight measurements of transition using the sublimating chemicals, response

time is sufficiently rapid that constant speeds and altitudes can be flown, and weight changes have an insignificant effect on transition location.

The use of an intentional boundary-layer trip, such as a very small piece of tape located within 6 in. of the leading edge, is a useful method of providing a "calibrated" indication of the rate of transition pattern development in the chemical coating. When the chemical pattern appears mature, the descent and approach should be flown as near to the indicated test speed and as close in to the landing as is safe. Since at most test conditions of interest, pattern development times are greater than 10 minutes, ample time is usually available for normal approaches and landings.

Selection of Chemicals

Selecting an appropriate chemical for a given flight condition requires an understanding of the chemical process involved. The rate of sublimation is simply the rate of transport of a foreign gas through the boundary layer. Thus, the rate of mass transfer will depend on the surface concentration of the diffusing gas. The sublimation rates can be approximated by considering the relationships between diffusion, heat transfer, and skin friction. This paper covers only the principal equations for predicting sublimation rates; a more detailed analysis appears in reference 5.

The rate at which mass is transferred across a unit area of the surface, g_s , is given by

$$g_s = K_g \rho_\infty V_\infty (\psi_s - \psi_\infty) \quad (1)$$

where K_g is the local mass transfer coefficient, ρ_∞ and V_∞ are the free-stream density and velocity, and ψ_s and ψ_∞ are the foreign gas concentrations at the surface and the free stream, respectively. The concentrations can be represented by the general form

$$\psi = \frac{\rho}{\rho_\infty} \quad (2)$$

where ρ is the density of the diffusing vapor. For the sublimation process occurring in air, ψ_∞ can be taken as zero; however, determination of ψ_s is less obvious. There are two stages for the sublimation of a substance into a stream of air (ref. 5). The first stage is purely molecular and takes place in a very thin layer near the surface. It involves a continuous evaporation and recondensation of gas molecules in the surface layer of chemicals. The second stage can be represented by the diffusion through the boundary layer of those molecules which escape from the surface layer. The number of molecules that do escape can be determined by the difference between the partial pressure of the vapor at the surface and the saturation pressure. It has been shown (ref. 5) that the concentration at the surface corresponds closely to saturation. This can account for the fact that relatively smaller amounts of molecules are carried away from the surface as compared to the larger quantity evaporating and recondensing in the surface layer. For the sublimation of substances used for boundary-layer observation, the concentration at the surface can be approximated by

$$\psi_s = \frac{m p_s}{m_\infty p_\infty} \quad (3)$$

where m and m_∞ are the molecular weights of the substance and the air, respectively, p_s is the absolute vapor pressure, and p_∞ is the free-stream static pressure.

By combining equations (1) and (3) and assuming that $\psi_\infty = 0$, the rate of sublimation can be rewritten as

$$g_s = K_g p_\infty V_\infty \left(\frac{m}{m_\infty} \right) \left(\frac{p_s}{p_\infty} \right) \quad (4)$$

Rearranging equation 4 using the ideal gas law yields

$$g_s = \frac{K_g}{R} \left(\frac{m}{m_\infty} \right) \frac{V_\infty p_s}{T} \quad (5)$$

For most liquids and solids, the variation of vapor pressure with temperature will follow the Clasius-Clapeyron law and is expressed as

$$\log_{10} p_s = -52.23 \frac{a}{(T + b)} + c \quad (6)$$

where p_s is the vapor pressure in millimeters of Hg at temperature T in $^{\circ}\text{C}$, and a , b , and c are constants for a particular substance. Approximate values of a , b , and c for the four solids selected as suitable boundary-layer transition indicators are taken from references 6 and 7 and are reproduced in Table 2. It must be mentioned here that values of p_s for a particular substance are not always consistent from one source to another. Some of these differences result from the difficulty of determining very low (at $T < 0^{\circ}\text{C}$)

Table 2. Vapor Pressure Constants for Selected Sublimating Chemicals

Chemical Substance	a	b	c
Naphthalene	30.759	187.22	6.846
Biphenyl	53.942	273.10	8.221
Acenaphthene	54.279	273.10	8.033
Fluorene	56.615	273.10	8.059

vapor pressures. Figure 2 shows the relation between vapor pressure and temperature from equation (6) over a range of temperatures compatible with flight operations.

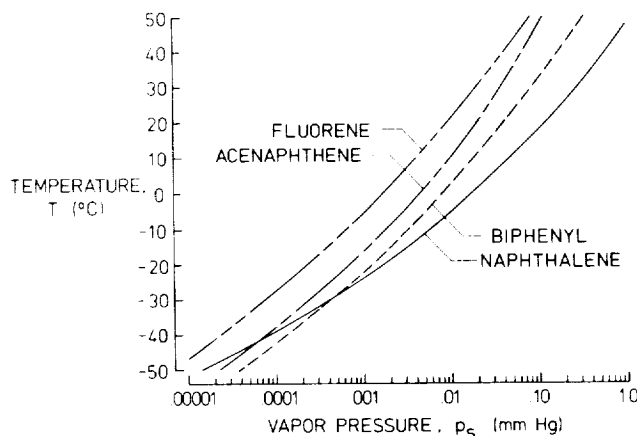


Figure 2.- Vapor pressures of sublimable solids.

For first approximations, the local mass transfer coefficient K_g is proportional to the local skin friction. In regions of high skin friction such as near the stagnation or attachment line or in the turbulent boundary layer, values of the local mass transfer coefficient will also be high. A complete description and analysis of this mechanism are available in reference 5.

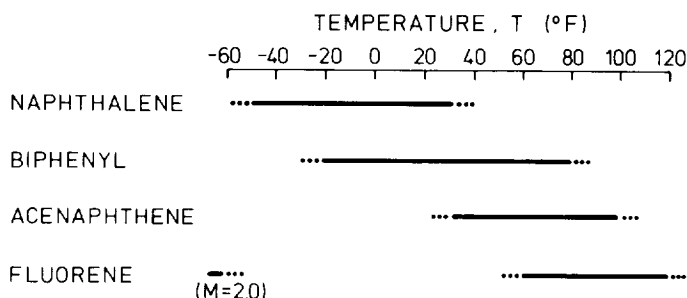
Based on past flight experiments, a practical summary is provided in figures 3 and 4 to guide selection of suitable chemicals for given test conditions. These recommendations will allow reasonable times for chemical pattern development at the test conditions and still provide adequate time for off-condition (climb and descent) portions of a flight profile. As given by equation 5, the rate of sublimation is proportional to ambient temperature, free-stream velocity, and local skin friction.

Figure 3 presents the operating temperature ranges of the four chemicals. Each solid bar represents typical limits, while the dashed ends suggest variability resulting from coating thickness. For the fastest sublimating solid, naphthalene, the useful temperature range at subsonic speeds is from $-50^{\circ}\text{F} < T < 32^{\circ}\text{F}$. Biphenyl and acenaphthene have subsonic temperature ranges of $-20^{\circ}\text{F} < T < 80^{\circ}\text{F}$ and $32^{\circ}\text{F} < T < 100^{\circ}\text{F}$, respectively. A subsonic temperature range for fluorene would be $60^{\circ}\text{F} < T < 120^{\circ}\text{F}$. The additional data point for fluorene at

the low temperature was for a supersonic aircraft ($M = 2.0$) tested by McTigue et al. (ref. 4). One of the factors that allow the use of sublimating chemicals at supersonic speeds is that the adiabatic wall temperature rises with compressibility. Since the chemicals are affected by this wall temperature, rates of sublimation are higher than would be normal at the free-stream temperature. The relationship between the adiabatic wall temperature and the free stream is

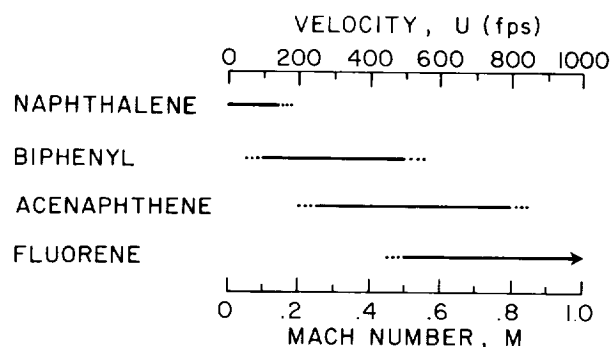
$$T_{aw} = T \left(1 + R \left(\frac{\gamma - 1}{2} \right) M^2 \right) \quad (7)$$

where γ is taken as 1.4 and R is the recovery factor. For a laminar boundary layer, the recovery factor is approximately 0.84, whereas for a turbulent boundary layer, the recovery factor is approximately 0.88. These suggested practical temperature ranges are based on the experiences of the author and on other published flight results.



- SUBLIMATION RATE IS ALSO PROPORTIONAL TO DYNAMIC PRESSURE (SKIN FRICTION)

Figure 3.- Temperature operating ranges for selecting sublimable chemicals.



- BASED ON SEA LEVEL STANDARD DAY CONDITIONS

Figure 4.- Velocity operating ranges for selecting sublimating chemicals.

As previously mentioned, the free-stream velocity affects the sublimation rate of a particular chemical. Based on the author's experience, suggested practical velocity ranges for each of the selected chemicals are presented in figure 4. These ranges are valid for sea-level standard day conditions. It is important to remember that the solid bar represents typical limits with standard coating thicknesses. Naphthalene can be used up to about 150 fps. Biphenyl works well in the low subsonic range of 50 fps to 500 fps, whereas acenaphthene is useful from 250 fps on up to transonic speeds of around 800 fps. A practical velocity range for fluorene would start from around 500 fps and go up to supersonic speeds.

The transition mechanism or mode can be determined by analysis of the chemical patterns which develop. Typical patterns for four modes of transition are shown in figure 5. Tollmien-Schlichting instability transition is characterized by a ragged transition line. A crisp straight line is indicative of the presence of




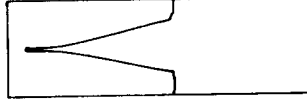
TRANSITION MODE	TYPICAL PATTERN
INSTABILITY	
LAMINAR SEPARATION	
VORTICITY	
ROUGHNESS	

Figure 5.- Transition mode characteristics in sublimating chemical patterns.

laminar separation. When there are streamwise striations in the chemical coating followed by a very jagged transition line, crossflow or Görtler instability is the transition mechanism. The fourth type of transition pattern is formed by roughness. A typical shape would be a thin trail behind the element quickly followed by a turbulent wedge, usually having an included angle of about 15°.

Sublimating Chemical Flow Visualization Examples

Sublimating chemicals have been used extensively in recent years by NASA Langley personnel to document boundary-layer transition locations in flight on a variety of aircraft. Complete documentation of the results of the flight tests is presented in reference 8. The sublimating chemical technique has been used successfully on all surfaces of an aircraft including wings, fuselages, empennages, and propellers.

Figure 6 shows a chemical pattern on the lower surface of a wing. The unit Reynolds number for the test was $R' = 1.9 \times 10^6 \text{ ft}^{-1}$, and the chemical was acenaphthene. The figure shows the effect of insect strikes, propeller slipstream, and roughness in the form of inspection cover plates, screws, and selected tape trips on boundary-layer transition. There were several additional insect strikes which did not cause transition, whereas the ones shown did, as indicated by the turbulent wedges in the chemical pattern. The middle inspection cover had an aft-facing step which caused boundary-layer transition. Although

it cannot be seen, the wing root caused transition because of the screw heads holding the plate rather than by the step height. Two additional turbulent wedges appear from intentional tape trips which served to calibrate the photograph. Another noticeable effect is that the propeller slipstream caused the mean transition front to move slightly forward. The natural transition front shows the smooth, uniform pattern characteristic of laminar separation.

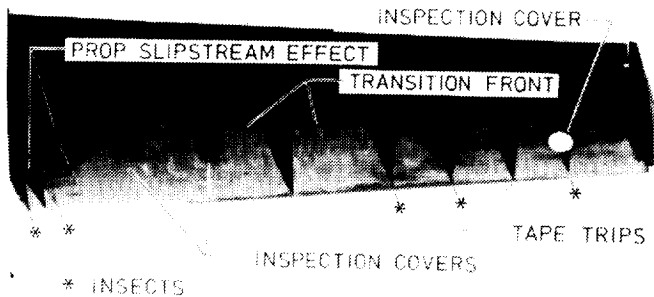


Figure 6.- Boundary-layer transition on a wing lower surface indicated by sublimating chemicals (acenaphthene), $R' = 1.9 \times 10^6 \text{ ft}^{-1}$ (ref. 8).

As noted previously above, it is possible to measure the extent of laminar flow on a rotating propeller. Figure 7 shows an example of the suction side of a propeller and its boundary-layer transition location. Another useful application of sublimating chemicals for flow visualization is in determining crossflow vortices, as shown in figure 8. The figure shows the development of crossflow vortices in the laminar boundary layer on the lower surface of a 27° swept wing at $R' = 2.4 \times 10^6 \text{ ft}^{-1}$. Prior to causing boundary-layer transition, the vortices were spaced at 8-10 per inch.

In separate unpublished tests, a comparison between oil flows and

sublimating chemicals was conducted in flight and in a wind tunnel. The results showed that sublimating chemicals indicate the location of turbulent reattachment following laminar separation.

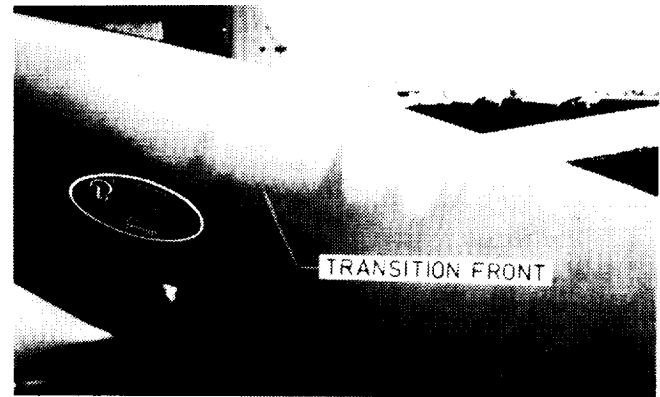


Figure 7.- Boundary-layer transition on the suction side of a propeller indicated by sublimating chemicals (acenaphthene), $R' = 2.77 \times 10^6 \text{ ft}^{-1}$.

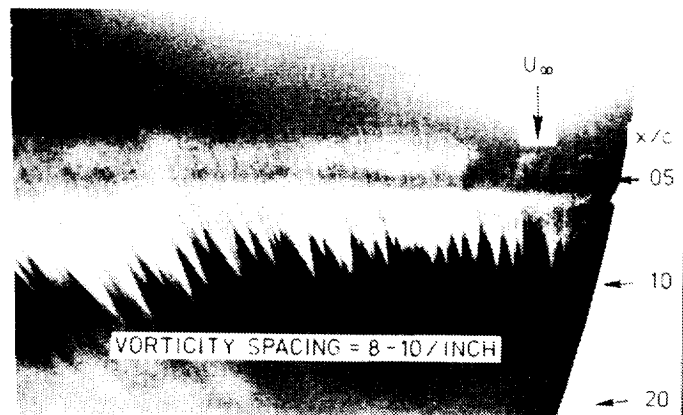


Figure 8.- Crossflow vortices indicated by sublimating chemicals (acenaphthene), $\Lambda = 27^\circ$, $R' = 2.4 \times 10^6 \text{ ft}^{-1}$.

Safety Precautions

There are several precautions which should be followed in order to insure safe use of sublimating chemicals. The chemicals discussed here were selected because of their low health hazards. However, these chemicals should still

be treated with caution. Persons within close use of the chemicals should wear an organic-vapor-type respirator (carbon filter). Eye and skin contact should be avoided whenever possible. Rubber gloves are recommended for handling. (Wash after use.) Always provide adequate ventilation when applying the chemicals. Biphenyl and naphthalene have been found to have low short-term and low long-term toxicity. Currently, fluorene and acenaphthene are known to have low short-term toxicity, but long-term toxicity has not been extensively studied. For further health safety information on these and other chemicals, consult the American Society for Testing and Materials or request a materials safety data sheet from the chemical supplier.

A recent safety alert has been announced regarding the use of 1,1,1-trichloroethane and other halogenated hydrocarbons in pressurized fluid systems having aluminum or galvanized wetted parts. Under certain circumstances, these solvents can corrode the aluminum or galvanized parts. In pressurized spraying systems, this corrosive action could result in a pressure vessel explosion. Unless a stainless steel canister and spray gun are used, a siphon cup sprayer should be used when applying the chemical with a halogenated hydrocarbon solvent. Inspect aluminum parts regularly for corrosion. Acetone can be used as a solvent; however, it does affect fiberglass and plexiglass and is a greater fire hazard than 1,1,1-trichloroethane. Proper cleaning of any fluid system will minimize the potential hazard. For further information on potential corrosion hazards, it is best to consult the manufacturer of the spray equipment.

OIL FLOW

Description of Technique

A second useful flow visualization technique for determining the state and nature of the flow over a surface is that of oil flow. Oils can identify regions of laminar and turbulent flow, regions of separated flow, location of shocks, and the location of laminar separation bubbles. One advantage of field flows over sublimating chemicals is the ability to detect laminar separation bubbles.

The technique of applying and using oils differs somewhat from that for sublimating chemicals. The oil is brushed onto the surface to be tested. The aircraft is then flown to the desired flight conditions and held there until an oil pattern has developed. The oil will flow in the direction of the surface flow, collecting in regions of reverse flow, as shown in figure 9.

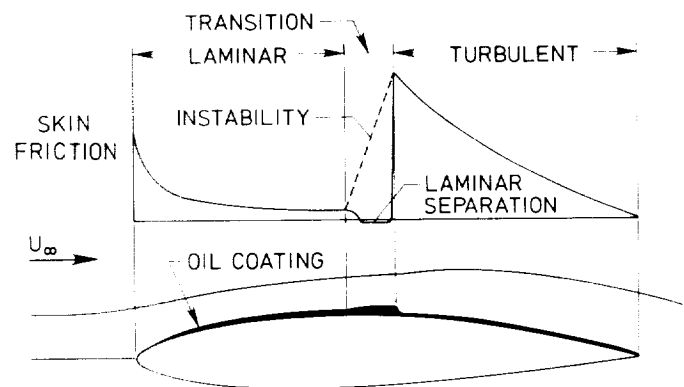


Figure 9.- How oil flows indicate boundary-layer transition.

Rapid movement of the oil will occur in regions of high skin friction and shear. Ambient temperature has a large effect on the flow characteristics of

the oil. The oil becomes less responsive at lower temperatures which occur at higher altitudes. This requires that the flight test conditions be held longer to insure that the oil patterns have adapted to the flow field. Unlike sublimating chemicals, with oil any photographs of the developed pattern must be taken during flight at the desired test conditions, since transition patterns in oil coatings are difficult to preserve through off-condition flight regimes. For this same reason, the use of a less viscous oil may not help the low temperature effect, since the climb portion of the flight would generally remove the thinner oils. For most flight conditions, the use of a 1:1 mixture of AMS/Oil Para-Synthetic and Mobil 1, combined with a pigment to provide a contrast with the surface, has been recommended (ref. 3). Suggested pigments include ferric oxide (FeO_2) for visualization on lighter surfaces and titanium dioxide (TiO_2) for contrast on darker surfaces. Useful ratios of pigment to oil are 1:10 for ferric oxide and 1:1 for titanium dioxide. The pigment should be completely dissolved into the oil before application to any surface. Further information on the use of oil flow can be obtained from reference 3.

Oil Flow Visualization Examples

Some of the results of Curry et al. (ref. 3) in using oils for in-flight flow visualization are reproduced here. Figure 10 shows an oil flow pattern indicating boundary-layer transition. The unit Reynolds number for this test was $R' = 630,000 \text{ ft}^{-1}$, and the oil was the mixture of AMS/Oil and Mobil 1 recommended above. The

effect of fixed transition, followed further downstream by a region of flow separation, is also shown. An example of a shock location indicated by oil flow is shown in figure 11. For the faster speed, $M = .85$, $R' = 2.9 \times 10^6 \text{ ft}^{-1}$, a more viscous oil was used.

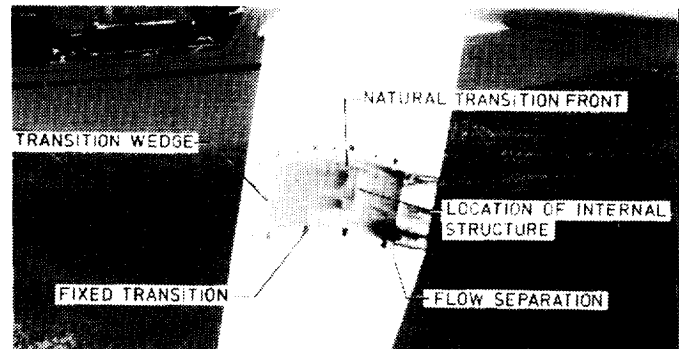


Figure 10.- Boundary-layer transition indicated by oil flow, $R' = 0.63 \times 10^6 \text{ ft}^{-1}$.

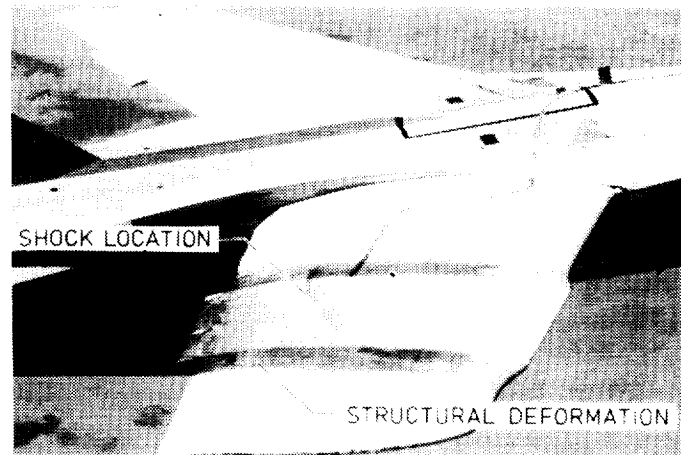


Figure 11.- Shock wave location indicated by oil flow, $M = 0.85$, $R' = 2.9 \times 10^6 \text{ ft}^{-1}$ (ref. 3).

CONCLUSIONS

Combined use of both oil flows and sublimating chemicals provides extensive boundary-layer data for use in design validation or certification

flight testing. Each method of flow visualization has its advantages and disadvantages. Oil flows can be used to determine boundary-layer transition, shock wave locations, regions of separated flow, and surface flow direction. However, they must be photographed in flight following pattern development and are somewhat untidy. Sublimating chemicals are useful for visualizing boundary-layer transition patterns from several modes of transition, including Tollmien-Schlichting instability, laminar separation, crossflow instability, and transition due to roughness. With the advent of new aircraft utilizing laminar flow for drag reduction, flow visualization is a valuable diagnostic tool to supplement other analytical measurements.

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